Neutrino deuteron reaction in the heating mechanism of core-collapse supernovae

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Abstract

We examine a potential role of the neutrino deuteron reactions in the mechanism of supernova explosion by evaluating the energy transfer cross section for the neutrino heating. We calculate the energy loss rate due to the neutrino absorptions through the charged-current process as well as the neutrino scattering through the neutral-current process. In so doing, we adopt a detailed evaluation of cross sections for the neutrino deuteron reactions with the phenomenological Lagrangian approach. We find the energy transfer cross section for the deuteron is larger than those for ^{3}H, ^{3}He and ^{4}He for neutrino temperatures ($T_\nu \sim 4$ MeV) relevant to supernova core. Because of the low energy threshold for the deuteron breakup, the energy transfer rate rapidly increases from low temperature, $T_\nu \sim 1$ MeV. This suggests that the neutrino deuteron reactions may contribute effectively to the heating mechanism during the dissociation of irons into light elements and nucleons in the shocked material of supernova core.

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I. INTRODUCTION

The reactions between neutrinos and nuclei play important roles in various phenomena in physics and astrophysics. The neutrino-nucleus interactions are crucial in physics of core-collapse supernovae through neutrino scattering, absorption and emission. Reliable evaluation of the rates of neutrino-nucleus interactions is necessary for the terrestrial neutrino detectors such as Super-Kamiokande and SNO [1, 2, 3, 4, 5, 6], for predicting the amount of elements produced in the nucleosynthesis through neutrino-processes [7, 8, 9], and for understanding the mechanism of supernova explosion[10, 11] after the core bounce of the gravitational collapse of massive stars.

In the neutrino heating mechanism, which is one of the key issues for the successful supernova explosion, the neutrino-nucleus interactions may contribute to the energy deposition in addition to the neutrino-nucleon interactions [11, 12]. In most of recent studies on supernovae, the shock wave launched by the core bounce stalls on the way and needs extra assistance to revive the outward propagation [13, 14]. Although the absorption of neutrino on the nucleon is the main mechanism of the energy deposition, nucleus can be an extra agent of the energy deposition through the absorption or scattering. An advantage of nuclei as targets is that neutrinos interact through the neutral-current (NC) as well as the charged-current (CC). Since the neutrinos of μ- and τ-types have relatively higher average energies than those of electron-type, they can have larger cross sections than those from the CC reactions for the low-energy electron-type neutrinos.

The neutrino heating through the neutrino-nucleus interactions has been proposed by Haxton and the average energy transfer cross section has been evaluated for the representative case of ^{4}He and ^{56}Fe [11]. Since the matter from outer layer free-falls down to the shock wave and is dissociated into ^{4}He and nucleons due to the shock heating, those two representative species are potential targets of neutrinos streaming from the central core. Although its influence on the supernova dynamics has been studied by numerical simulations under the spherical symmetry with those reaction rates [12], it was reported that their effect is too small to affect significantly the dynamics. In a recent study on the standing accretion shock-wave instability (SASI), Ohnishi et al. [15] have explored how the inelastic scattering of neutrinos with ^{4}He influence the outcome of shock dynamics by performing numerical simulations in two dimensions. An effect on the growth of instability toward the explosion is found only for the critical condition in which the dynamics of shock wave is marginal to the explosion and exploratory cases with enhanced reaction rates. The effect depends crucially on the cross section of the neutrino-^{4}He scattering and detailed evaluation based on theoretical models have been done recently [9, 16].

Recently, several authors pointed out the appearance of light elements (A ≤ 3) other than ^{4}He in supernova environment, and its potential role on the supernovae through the neutrino interactions[17, 18, 19]. O'Connor et al. [17] studied the abundance of tritons and ^{3}He in dense matter and evaluated the neutrino reaction rates. The A=3 nuclei can be more abundant than ^{4}He and nucleons, and its energy transfer rate can be larger than that of ^{4}He for certain conditions of proton fraction, density and temperature. Arcones et al. [19] used a statistical model and studied the abundance of light elements in the neutrino-driven flows after the explosion. They demonstrated that the neutrino reactions on the light elements can have an influence on the spectra of neutrinos emitted from the surface of proto-neutron stars.

So far, attention has been paid to the neutrino reactions on A=3, 4 nuclei only. Sumiyoshi

and Röpke [18] studied the composition of light elements in supernovae by including the deuteron, A=3, 4 nuclei and others in many-body calculations (See also [19]), and found that the deuteron can also appear abundantly in some regions of supernova environment. Since the cross section of the neutrino-deuteron reaction is much larger than those for ^{3}H, ^{3}He and ^{4}He, the energy deposition through the deuteron may significantly contribute to the neutrino heating during the dissociation of iron nuclei into light elements and nucleons.

In this paper, we examine the possible role of the deuteron by evaluating the neutrino heating rates through the neutrino-deuteron (νd) interactions. For the estimation of the νd reaction cross sections, we adopt the standard nuclear physics approach(SNPA)[3, 4]. In SNPA, we consider the nuclear current consisting of one-body impulse terms and two-body exchange-current terms, and evaluate their matrix element with the nuclear wave functions generated with a high-precision NN potential. The reliability of our SNPA has been extensively tested by comparisons of calculated observables with available data of photo-processes, and also from a good agreement with the results of the effective field theory approach[4, 6] for the solar neutrino energy. We calculate the average energy transfer rates (and the heating rate) by using the Fermi distribution of the neutrino energy, and examine an effect of the νd reaction on the supernova dynamics in the heating region. We have in our mind here the typical situation realized in the region between the stalled shock wave and the proto-neutron star surface, where neutrinos are emitted with spectra close to the one under the equilibrium parametrized by the local temperature. We consider the neutrino reactions on the deuteron through both the CC and NC, covering the deuteron breakup and scattering.

We show that the energy transfer rates through the νd reactions are much larger than those of ^{3}H, ^{3}He and ^{4}He for the typical range of the neutrino temperature, especially at low temperature (energy) because of the lower breakup threshold. This suggests that the deuteron can contribute, as an extra agent, to the neutrino heating in supernova dynamics. The current finding urges ones to examine its effects on the supernova explosion by implementing the νd reactions as well as a detailed treatment of the mixture of light elements in supernova simulations.

II. FORMULATION

We are concerned with the charged-current (CC) and neutral-current (NC) $\nu(\bar{\nu})d$ reactions listed in the following equations.

$$\nu_e + d \rightarrow e^- + p + p \quad [\nu CC] \tag{1}$$
$$\bar{\nu}_e + d \rightarrow e^+ + n + n \quad [\bar{\nu} CC] \tag{2}$$
$$\nu + d \rightarrow \nu + p + n \quad [\nu NC] \tag{3}$$
$$\bar{\nu} + d \rightarrow \bar{\nu} + p + n \quad [\bar{\nu} NC] \tag{4}$$
$$\nu/\bar{\nu} + d \rightarrow \nu/\bar{\nu} + d \quad [\nu/\bar{\nu} scatt] \tag{5}$$

In the supernova environment, the CC reactions act as an absorber of the neutrino, and the neutrino energy is deposited to the rest of compositions of supernova matter. For the NC reactions, the energy difference between the incoming and outgoing neutrinos is the energy transfer to the matter.

The interaction Hamiltonian for semileptonic weak processes is given by the product of

the hadron current (J_λ) and the lepton current (L^λ) as

$$H_W^{CC} = \frac{G_F' V_{ud}}{\sqrt{2}} \int d\boldsymbol{x}[J_\lambda^{CC}(\boldsymbol{x})L^{CC,\lambda}(\boldsymbol{x}) + \text{h. c.}] , \tag{6}$$

for the CC process and

$$H_W^{NC} = \frac{G_F'}{\sqrt{2}} \int d\boldsymbol{x} \ [J_\lambda^{NC}(\boldsymbol{x})L^{NC,\lambda}(\boldsymbol{x}) + \text{h. c.}] , \tag{7}$$

for the NC process. Here G_F' is the Fermi coupling constant, and V_{ud} is CKM matrix element. For the weak coupling constant we adopt $G_F' = 1.1803 \times 10^{-5} \text{GeV}^{-2}$ [4]. The CKM matrix element is taken to be $V_{ud} = 0.9740$.

The hadronic CC is written as

$$J_\lambda^{CC}(\boldsymbol{x}) = V_\lambda^{1\pm i2}(\boldsymbol{x}) + A_\lambda^{1\pm i2}(\boldsymbol{x}), \tag{8}$$

where V_λ and A_λ denote the vector and axial-vector currents, respectively. The $J_\mu^{1\pm i2}$ for the $\nu/\bar{\nu}$-reaction denotes $J_\mu^1 \pm iJ_\mu^2$, where J^i is the ith component of the isovector current. The hadronic NC is given by

$$J_\lambda^{NC}(\boldsymbol{x}) = (1 - 2\sin^2\theta_W)V_\lambda^3(\boldsymbol{x}) + A_\lambda^3(\boldsymbol{x}) - 2\sin^2\theta_W V_\lambda^s(\boldsymbol{x}), \tag{9}$$

where θ_W is the Weinberg angle and V_λ^s is the isoscalar part of the vector current. The lepton currents, $L^{CC,\lambda}$ and $L^{NC,\lambda}$, are well known.

The nuclear current consists of one-nucleon impulse approximation (IA) terms and two-body meson exchange-current (EXC) terms. The IA current is determined by the single-nucleon matrix element of J_λ with the standard parametrization. For the axial vector EXC (A_{EXC}), we consider the pion-pair current, rho-pair current, pion- and rho-exchange Δ currents, $\pi - \rho$ current following Refs. [20, 21]. The strength of A_{EXC} is adjusted to reproduce the experimental value of the triton beta decay rate. Regarding the vector EXC, we take into account the pion-pair, pionic and pion- and rho-exchange Δ currents. As discussed in [3], the model of the nuclear vector current leads to $np \to d\gamma$ total cross sections that agree very well with the experimental values. The expressions of IA, EXC and the coupling constant used in this work are given in Ref. [3, 4].

The cross sections for the $\nu/\bar{\nu}(k) + d(P) \to l(k') + N_1(p_1') + N_2(p_2')$ in the laboratory system are calculated following the standard procedure. We obtain the cross section for the CC reaction as

$$d\sigma = \sum_{\bar{i},f} \frac{\delta^{(4)}(k + P - k' - P')}{(2\pi)^5} \frac{G_F'^2 V_{ud}}{2} F(Z, E_\ell') \ |l^\lambda j_\lambda^{CC}|^2 d\boldsymbol{k}' d\boldsymbol{p}_1' d\boldsymbol{p}_2', \tag{10}$$

where we have included the Fermi function $F(Z, E_l')$ to take into account the Coulomb interaction between the electron and the nucleons in the final state. The cross section for the NC reaction is written as

$$d\sigma = \sum_{\bar{i},f} \frac{\delta^{(4)}(k + P - k' - P')}{(2\pi)^5} \frac{G_F'^2}{2} |l^\lambda j_\lambda^{NC}|^2 d\boldsymbol{k}' d\boldsymbol{p}_1' d\boldsymbol{p}_2'. \tag{11}$$

We have used the matrix elements l^λ and j^λ defined as

$$j_\lambda = <NN(P')|J_\lambda(0)|d(P)>, \tag{12}$$
$$l_\lambda = <l(k')|L_\lambda|\nu/\bar{\nu}(k)> . \tag{13}$$

The cross section for the neutrino-deuteron elastic scattering $(\nu/\bar{\nu}(k) + d(P = 0) \rightarrow \nu/\bar{\nu}(k') + d(P'))$ is written as

$$\frac{d\sigma}{dk'} = \frac{k'}{k}\frac{M_d}{\pi}G_F'^2 4\sin^4\theta_W[A\cos^2\theta_L/2 + B\sin^2\theta_L/2], \tag{14}$$

where θ_L is the scattering angle of the neutrino in the laboratory system and is determined from the energies of the neutrinos in the initial(k) and the final(k') states as

$$\cos\theta_L = 1 - (k - k')M_d/(kk'). \tag{15}$$

Since the deuteron is an iso-scalar object, only the iso-scalar vector current of the hadronic NC contributes to the νd elastic scattering. Neglecting a small contribution from the strange form factor, the matrix element of the hadronic current can be expressed with the iso-scalar elastic electromagnetic form factors of the deuteron. The structure functions, A and B, can be expressed with the electromagnetic Coulomb monopole (G_C), magnetic dipole (G_M) and quadrupole (G_Q) form factors of the deuteron as

$$B = \frac{4}{3}\eta(1 + \eta)G_M^2 , \tag{16}$$
$$A = G_C^2 + \frac{8}{9}\eta^2 G_Q^2 + \frac{2}{3}\eta G_M^2 , \tag{17}$$

with $\eta = Q^2/4M_d^2$ and $Q^2 = (\boldsymbol{k} - \boldsymbol{k}')^2 - (E_\nu - E_\nu')^2$. We use the IA current to calculate the iso-scalar form factors. Since the dominant contribution to the elastic νd scattering is from G_C, effects of EXC is expected to be small in the energy region of our interest.

In our numerical calculation, we use the ANLV18 potential [22] to generate the deuteron and two-nucleon scattering wave functions. The NN partial waves up to $J = 6$ are included for the deuteron breakup reactions.

III.   RESULTS AND DISCUSSIONS

First we present the energy dependence of the total cross sections for the reactions in Eqs.(1)-(5). The total cross section for the neutrino and anti-neutrino deuteron reactions are shown in Figs. 1 (a) and (b), respectively. The neutrino CC reaction (νCC) gives the largest cross sections which are about 1/3 (1/2) of the neutrino-nucleon CC reaction at $E_\nu = 10(50)$MeV. The νd elastic cross section is very small compared with that of νCC. In the high energy region around the pion production threshold ($E_\nu \sim 140$MeV), the pion production cross sections can be safely neglected[23].

An interesting quantity relevant to the supernova physics is a thermal average of the energy transfer cross section defined by[11]

$$<\sigma\omega>_{T_\nu} = \int dE_\nu f(T_\nu, E_\nu)\sigma\omega(E_\nu) . \tag{18}$$
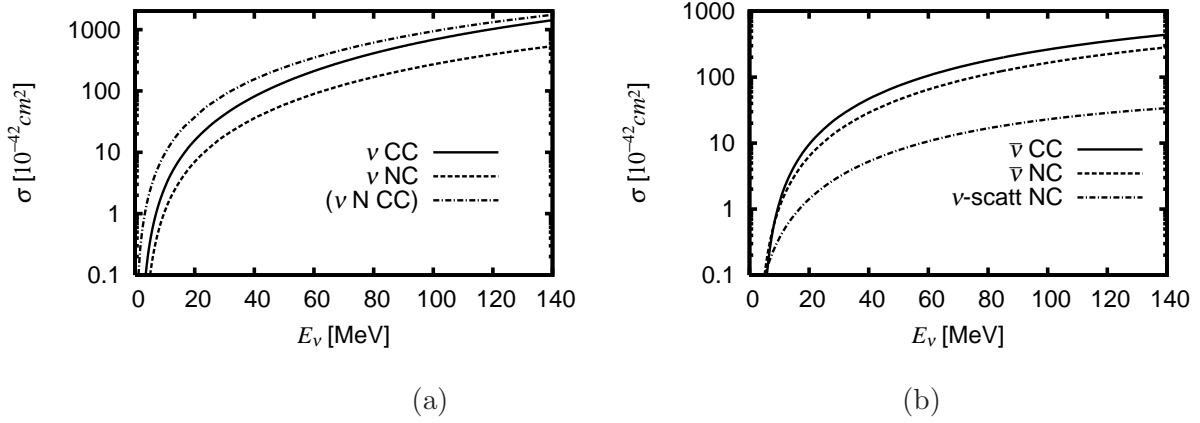
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FIG. 1: Total cross sections for the neutrino-deuteron reactions. The solid and dotted curves show the cross sections for (a) $\nu_e d \rightarrow e^- pp$ (νCC) and $\nu d \rightarrow \nu pn$ (νNC), respectively and (b) $\bar{\nu}_e d \rightarrow e^+ nn$ ($\bar{\nu}$CC) and $\bar{\nu} d \rightarrow \bar{\nu} pn$ ($\bar{\nu}$NC), respectively. The dot-dashed curves show (a) the cross sections for $\nu + n \rightarrow e^- + p (\nu N CC)$ and (b) the cross sections for $\nu + d \rightarrow \nu + d$ ($\nu - scatt$).

We assume here a Fermi-Dirac distribution for the neutrino, having in mind the neutrino flux from the supernova core. At the temperature T_ν with zero chemical potential, a neutrino with the energy E_ν distributes as

$$f(T_\nu, E_\nu) = \frac{N}{T_\nu^3} \frac{E_\nu^2}{e^{E_\nu/T_\nu} + 1} \ . \tag{19}$$

The energy transfer cross section $\sigma\omega(E_\nu)$ is evaluated by integrating the differential cross section multiplied by the energy loss of the incident neutrino with respect to the energy of the final lepton:

$$\sigma\omega(E_\nu) = \int dE_l' \frac{d\sigma}{dE_l'} E_\nu \ , \tag{20}$$

for the CC reaction (absorption) and

$$\sigma\omega(E_\nu) = \int dE_\nu' \frac{d\sigma}{dE_\nu'} (E_\nu - E_\nu') \ , \tag{21}$$

for the NC reaction (scattering). This quantity is important for evaluating the neutrino heating behind the shock wave in the supernova. The energy of the incident neutrino is transferred to the matter (deuterons, nucleons, electrons/positrons) via the absorption (CC) or down-scattering ($E_\nu' < E_\nu$, NC). Note that the electrons, positrons and photons are regarded as a part of *matter*, being in thermal and chemical equilibrium with nucleons and nuclei in the supernova core, while the neutrinos are separately treated in the neutrino transfer calculations.

The integrand of the average energy transfer cross sections,
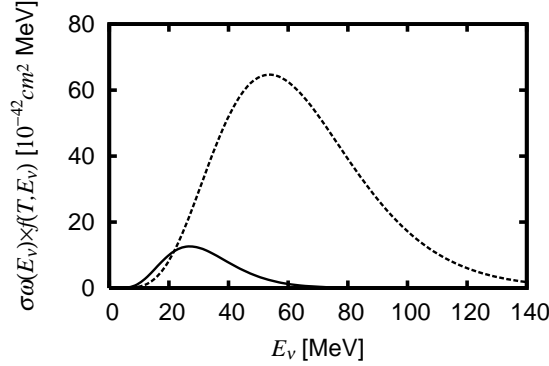
$$f(T_\nu, E_\nu)\sigma\omega(E_\nu) \ , \tag{22}$$

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FIG. 2: Energy (E_ν) dependence of the energy transfer cross section for the CC νd reaction multiplied by the Fermi-Dirac distribution function at $T_\nu = 5$ MeV(solid curve) and 10 MeV(dashed curve).

for ν CC is plotted in Fig. 2 as a function of the incident neutrino energy, E_ν, at $T_\nu = 5$ and 10MeV. The main contribution for the average cross section is from $E_\nu \sim 20(60)$MeV at $T_\nu = 5(10)$ MeV. We note that the contribution from the high energy tail of $f\sigma\omega$ is appreciable.

Finally our results on the thermal average of the energy transfer cross sections are shown in Fig. 3 and Table I. The largest cross section is due to νCC which is almost the same magnitude as $\bar{\nu}$CC. The CC cross sections are an order of magnitude larger than the NC cross sections. We remark that the νd cross sections are appreciable even at relatively low temperature beyond the breakup threshold energy. This is a characteristic feature of the νd reaction involving the breakup of the weakly bound state with 2.2MeV binding energy. The rapid increase of the cross section at low energy makes the deuteron more preferable target than the other nuclear species in the supernova environment.

In order to discuss the contribution of the deuteron in the neutrino heating mechanism through a comparison with other neutrino-nucleus processes, we evaluate the average energy transfer rate per nucleon through the neutrino and anti-neutrino reactions defined by

$$< \sigma\omega >^{CC} = \frac{1}{2A}[< \sigma\omega >_{\nu CC} + < \sigma\omega >_{\bar{\nu} CC}] , \tag{23}$$

$$< \sigma\omega >^{NC} = \frac{1}{2A}[< \sigma\omega >_{\nu NC} + < \sigma\omega >_{\bar{\nu} NC} + < \sigma\omega >_{\nu scatt} + < \sigma\omega >_{\bar{\nu} scatt}] , \tag{24}$$

where the factor 1/2 comes from the average over the neutrino and anti-neutrino. We show the calculated average energy transfer rate in Fig. 4. For comparison we show the average energy transfer rate for A=3, 4 nuclei. For the CC reactions, the $\bar{\nu}$-^{3}H rate is calculated from $\bar{\nu}$-^{3}H cross section given in Ref. [19] and the ν-^{4}He rate is taken from Ref. [11]. For the NC reactions, we take the values for the ν-^{3}He rate from Ref. [17] and the ν-^{4}He rate from Ref. [16]. It is remarkable that the average energy transfer cross sections for the νd reaction is significantly larger than those for ^{3}H, ^{3}He and ^{4}He for the temperature range relevant to the supernova core. The νd rate is much larger at low temperature because of the low threshold energy of the deuteron as discussed previously. In the case of the CC reaction the νd rate dominates, being larger than those for A=3, 4 nuclei by orders of magnitude.

The large energy transfer rate of the deuteron at the wide range of the temperature suggests that the deuteron is potentially an important target for the neutrino heating mechanism in supernovae. The average energy transfer cross section for the CC reaction is sufficiently large to yield a significant heating rate for moderate neutrino temperatures. For example, the average energy transfer cross section for the CC reaction is larger than 10^{-40} cm^{2}MeV at $T_\nu \geq 4$ MeV, and gives a significant contribution to the heating rate in addition to the contribution of the neutrino-nucleon reactions. According to the expressions of the heating rate given by Haxton [11], the heating rate due to the νd reactions for ν_e and $\bar{\nu}_e$ amounts to 99.1 MeV/sec per nucleon, assuming $T_{\nu_e}=T_{\bar{\nu}_e}=5$ MeV. The heating rate due to the νd reactions for μ and τ type neutrino is 55.6 MeV/sec per nucleon at $T_{\nu_\mu}=10$ MeV. These values are 25–44% of the heating rate, 223 MeV/sec per nucleon, due to the ν-nucleon reactions at the same neutrino temperature of 5 MeV for $\nu_e/\bar{\nu}_e$. In the above estimate, we assumed values of the neutrino luminosities ($L_\nu=10^{52}$ erg/sec) and the distance from the center (100 km) in the expression for the heating rate given in Ref. [11]. As the neutrino temperature is higher so does the heating rate, which makes the νd reactions more important.

We remark that the deuteron as well as other light elements can appear in hot and dense matter in the heating region between the proto-neutron star and the shock wave. The Fe-group nuclei falling from the outer layer are dissociated into ^{4}He and then nucleons at the shock wave. Through this dissociation, light elements ($A \leq 3$) including the deuteron can appear naturally in the hot environment [17, 18]. Although the nucleons, having larger cross sections than those for nuclei, are the major targets of the neutrino after the complete dissociation, the deuteron and other light elements can contribute to the neutrino heating as an extra absorber of the neutrino.

Light elements can be dominant targets in the case of enlarged shock radius due to the hydrodynamical SASI instability as shown by Ohnishi et al. [15] in multi-dimensional supernova simulations. In such case, the range of density and temperature is favorable to have abundant ^{4}He with enough advection time to have neutrino absorptions. In their study, the ν-^{4}He reactions may be crucial for the revival of shock wave in the marginal condition, but they require the enhanced ν-^{4}He reaction rates. Since the νd reaction rates is much larger than those of ^{4}He as we have seen, the deuteron may play a similar role instead of ^{4}He during its dissociation. It would be interesting to explore the effect of νd reactions in the multi-dimensional supernova simulations with a detailed evaluation of mixture of light elements. The environment with an elongated shock wave due to the SASI instability may prefer to have abundant deuterons together with ^{4}He. It has been shown that the deuteron appears ($\sim 1\%$) in the heating region behind the stalled shock wave in a realistic snapshot of central core after the bounce in the spherical supernova simulations [18].

Further studies on the suitable condition to have a sufficient amount of targets and a long enough reaction time periods are necessary to firm the possible role of neutrino-deuteron interactions for the success of supernova explosions. The systematic study of the abundance of light elements in hot and dense matter is now under way [24].

In summary: the neutrino-deuteron reactions may have a potential impact on the neutrino heating mechanism in core-collapse supernovae. The cross section is large even at low neutrino energies relevant to supernovae because of the low breakup threshold for the bound state. The energy transfer rate through the νd reactions is much larger than those of ^{3}H, ^{3}He and ^{4}He even at low neutrino temperature. If deuterons appear abundantly in the heating region, as ^{4}He in the SASI instability, they can contribute to the extra heating, which assists the revival of stalled shock wave. It is interesting to explore whether the νd heating can
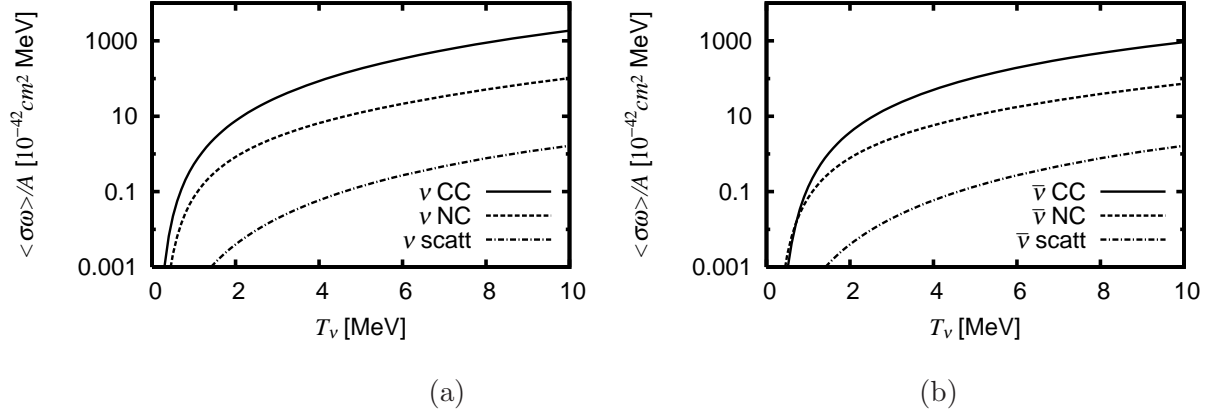
FIG. 3: Thermal average of energy transfer cross sections. The solid and dotted curves in (a) ((b)) show the cross sections for $\nu_e d \to e^- pp (\nu \text{CC})$ and $\nu d \to \nu pn (\nu \text{NC})$ ($\bar{\nu}_e d \to e^+ nn (\bar{\nu} \text{CC})$ and $\bar{\nu} d \to \bar{\nu} pn (\bar{\nu} \text{NC})$), respectively. The dot-dashed curve in (a) and (b) shows cross section for the elastic νd scattering.
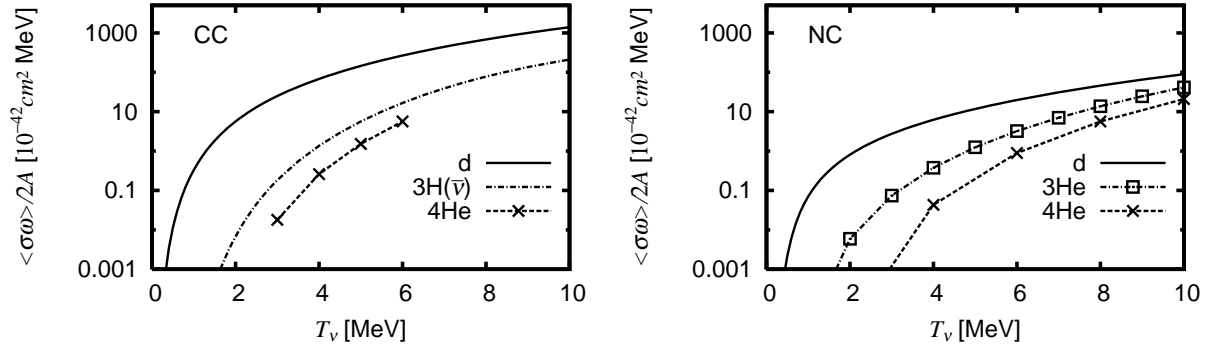

FIG. 4: Averaged energy transfer cross sections in unit of 10^{-42} MeV cm^2. The solid, dashed and dash-dotted curves show the νd, ν-^{4}He and ν-^{3}H (left panel) and ν-^{3}He (right panel) cross sections, respectively. (See the main text for the references on A=3, 4 nuclei cross sections.)

affect the dynamics of shock wave in realistic supernova simulations which take into account the mixture of light elements and the associated neutrino reactions.

The evaluated data of the νd energy transfer rate will be available on the web site for the neutrino deuteron reactions[25]. The data can be used to implement these processes into the heating rate in supernova simulations. Detailed neutrino differential cross sections based on the current theoretical approach can be provided for numerical simulations of the neutrino transfer which require the angle and energy variations. It will be also interesting to study the νd processes around the surface of proto-neutron stars and its influence on the neutrino nucleosynthesis. The other channels of weak processes on the deuteron are now under investigation.

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T_ν(MeV)	ν CC	$\bar{\nu}$CC	ν NC	$\bar{\nu}$ NC	ν Scatt.
1	1.06×10^0	2.68×10^{-1}	1.43×10^{-1}	1.38×10^{-1}	5.11×10^{-4}
2	1.51×10^1	7.50×10^0	1.66×10^0	1.56×10^0	7.95×10^{-3}
3	6.37×10^1	3.63×10^1	5.68×10^0	5.17×10^0	3.89×10^{-2}
4	1.71×10^2	1.01×10^2	1.31×10^1	1.15×10^1	1.18×10^{-1}
5	3.67×10^2	2.14×10^2	2.50×10^1	2.13×10^1	2.75×10^{-1}
6	6.79×10^2	3.87×10^2	4.28×10^1	3.51×10^1	5.42×10^{-1}
7	1.14×10^3	6.29×10^2	6.80×10^1	5.37×10^1	9.51×10^{-1}
8	1.78×10^3	9.49×10^2	1.02×10^2	7.80×10^1	1.53×10^0
9	2.64×10^3	1.35×10^3	1.48×10^2	1.09×10^2	2.31×10^0
10	3.73×10^3	1.85×10^3	2.06×10^2	1.46×10^2	3.30×10^0

TABLE I: Averaged energy transfer cross sections $< \sigma\omega >$ in unit of 10^{-42} MeV cm^2.

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